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MECHANICAL PROPERTIES OF FRICTION STIR WELDS IN Al2195-T8

By

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Abstract

An extensive study of the mechanical properties of friction stir welded Al-Li 2195 has been conducted by Lockheed Martin Michoud Space Systems under contract to NASA. The study was part of a development program in which weld parameters were defined for using FSW to assemble large-scale aluminum cryogenic tanks. In excess of 300 feet of 0.320" gage plate material was welded and tested. The tests include room temperature and cryogenic temperature tensile tests and surface crack tension (SCT) tests, nondestructive evaluation, metallurgical studies, and photostress analysis.

The results of the testing demonstrated improved mechanical properties with FSW as compared to typical fusion welding processes. Increases in ultimate tensile strength, cryogenic enhancement and elongation were observed with the tensile test results. Increased fracture toughness was observed with the SCT results. Nondestructive evaluations were conducted on all welded joints. No volumetric defects were indicated. Surface indications on the root side of the welds did not significantly affect weld strength. The results of the nondestructive evaluations were confirmed via metallurgical studies. Photostress analysis revealed strain concentrations in multi-pass and heat-repaired FSW's. Details of the tests and results are presented.

INTRODUCTION

Autogenous Friction Stir Welding (AFSW) has been developed for Al2195 under several studies conducted by Lockheed Martin for the National Aeronautics and Space Administration (NASA). AFSW is a solid state mechanical welding process for joining metals using no filler wire or weld gases. The largest Al-Li structure produced via FSW to date is the 27.5-ft. diameter 10-ft. long barrel assembly shown in Figure 1. The process is controlled by three primary parameters, pin tool rotation speed, travel speed and pin tool depth as illustrated in Figure 2.

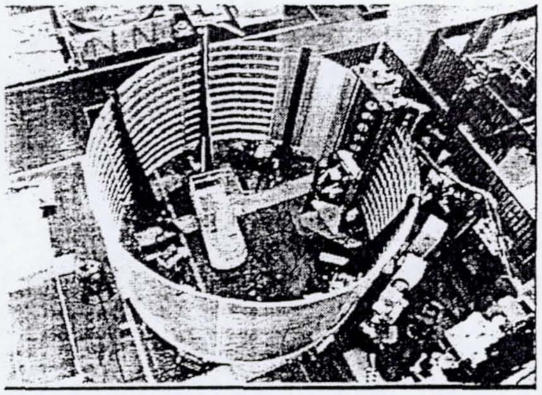

Figure 1. Al2195-T8 27.5-ft. diameter barrel assembled using Friction Stir Welding at MSFC

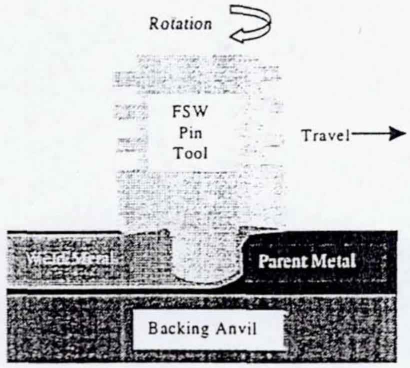

Figure 2. Schematic of Friction Stir Weld Tool Function

MATERIAL PROPERTIES TESTING

Development of a database for FSW material properties was initiated for Al2195 with the purpose of determining the following:

A. Basic mechanical properties data at room and liquid hydrogen temperatures.
B. Photostress evaluation of simulated FSW repair scenarios.
C. Metallurgical macro and micro evaluations.
D. Fracture toughness via Surface Crack Tension (SCT) testing and
E. NonDestructive Evaluation (NDE) of FSW.

Basic Mechanical Properties

Tensile tests were conducted using 1.0-inch wide strip tensile test specimens at room temperature (RT) and a 2.0-inch wide dogbone tensile test specimens at -423^0F. Larger 3.9" wide specimens were used for SCT tests, while 15" wide panels were used for FSW repair scenarios.

Several different material thicknesses, product forms and combinations of Al2195 with Al2219 were tested including:

A. 0.320-inch Al2195 plate-to-plate.
B. 0.650-inch Al2195 plate-to-plate.
C. 0.650-inch Al2219 forging to Al2195 plate.
D. 0.320-inch Al2219 forging to Al2195 plate and
E. Wide panel testing of weld repair scenarios for 0.320-inch Al2195 plate.

To date more than 300 mechanical properties tests, 30 SCT and SS tests and 4 different repair scenarios have been completed. These results show dramatic improvement over conventional fusion weld properties at room and cryogenic temperatures, in a weld that is remarkably free

from typical weld defects. In fact, FSW weld strength in Al2195 plate approaches parent material strength at -423^0F.

Scatterplots of mechanical properties test results are given in Figures 3 through 5. Separate test programs for weld schedule development, verification and larger scale (up to 14-ft. long) test panels produced the results shown in Figure 3. Note the similarity and consistency in both the room temperature and cryogenic (-423^0F) properties between the tests. A calculated cryogenic enhancement factor of 1.6 was determined as the ratio of CRYO strength to RT strength

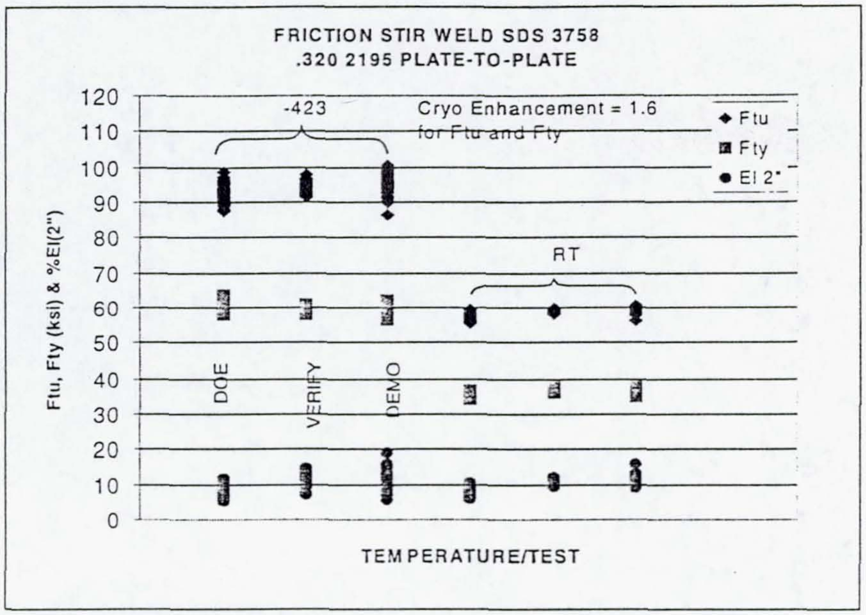

Figure 3. 0.320 DOE, verification and demonstration panel results.

Figure 4 displays data for FSW 0.32" and 065" Al2195 plate. The effect of strength versus thickness is seen noted at RT and CRYO. Yield strength and elongation data is consistent and reproducible, a characteristic not seen in conventional fusion welds.

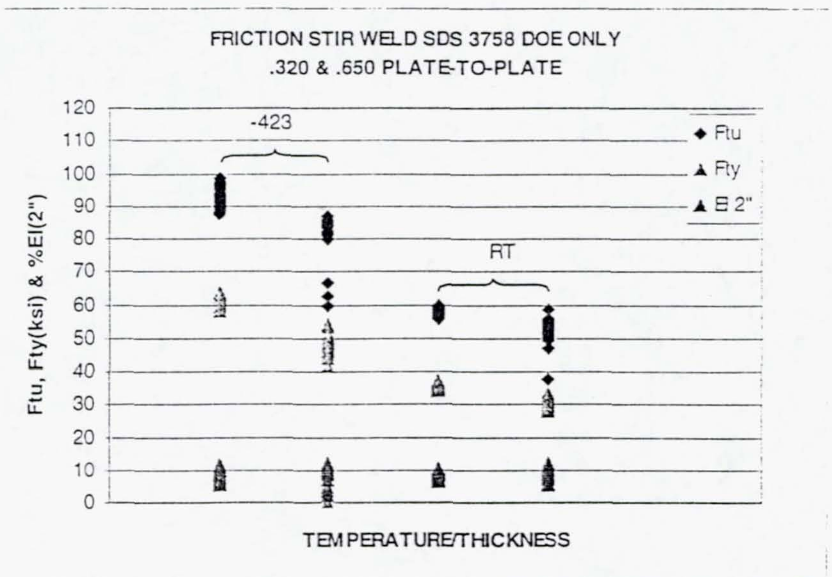

Figure 4. FSW 0.32 and 0.65 Al2195 plate

Table 1 provides a summary of FSW results by alloy combination, thickness and product form. For comparison, properties for typical fusion welds in Al2195-T8 are given as well.

Table 1. FSW Average Tensile Properties

Product	Thick (in.)	RT n	RT Ftu(ksi)	RT Fty(ksi)	CRYO n	CRYO Ftu(ksi)	CRYO Fty(ksi)
2195 P	0.32	178	58.7	36.6	149	95.5	60.0
2195 P	0.65	48	52.5	30.7	32	82.1	48.0
2195P/2219F	0.32	12	47.4	25.5	12	80.8	39.9
2195P/2219F	0.65	12	44.5	24.0	12	77.2	35.4
2195P Fusion	0.32	---	44	---	---	58	---

Photostress of FSW Repair Scenarios in 15" Wide Panels

Photostress evaluation and mechanical properties data was collected from simulations of Friction Stir Weld Overlap, Friction Plug Weld (FPW) Repair, Friction Stir Repair and Fusion Weld Repairs. All testing was conducted on 0.32" thick X 15" wide FSW Al2195 plate. Standard 1.0" strip tensiles were also tested from these panels.

Figure 5 is a photostress graphic of an as welded (AW) FSW panel. The difference in photo strain level between top and bottom plates is due to a difference in thickness between the top (0.331") and bottom (0.318") plates. Little difference in the strain between the FSW metal and the base metal was noted at 25 ksi loading, however this changed as loading increased to 38 ksi. At 38 ksi loading the highest strain, 5110 micro strain (equals to 43 ksi apparent stress), was located at the trailing side of the friction stir weld. It is only 5 ksi higher than the remote loading stress (38 ksi), and suggests that the residual stress on friction stir welds is substantially lower than that on comparable fusion welds.

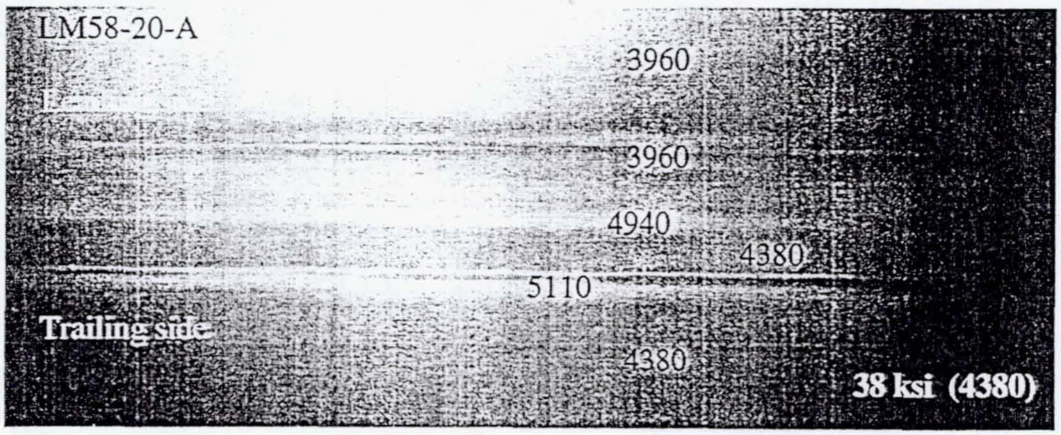

Figure 5. Isochromatic fringe pattern, Panel LM58-20-A, 38 ksi loading

(Values are in micro strain).

Photostress of FSW repairs showed the highest photo strain and lowest mechanical properties in fusion repairs made to FSWs. All other FSW repair methods used FPW as a closeout technique. Figure 6 is typical of the results for the FSW repairs and shows a 5" long FSW repair of an original FSW. Both the FSW plunge area and plug closeout revealed higher residual stress as demonstrated by higher photo strain on isochromatic fringes as shown in this view. The plunge is the start of the FSW repair weld, while a single FPW is used as a closeout. Fracture origins were located at the plunge area as well as the plug repair closeout when this panel was tested to failure at -423^0F.

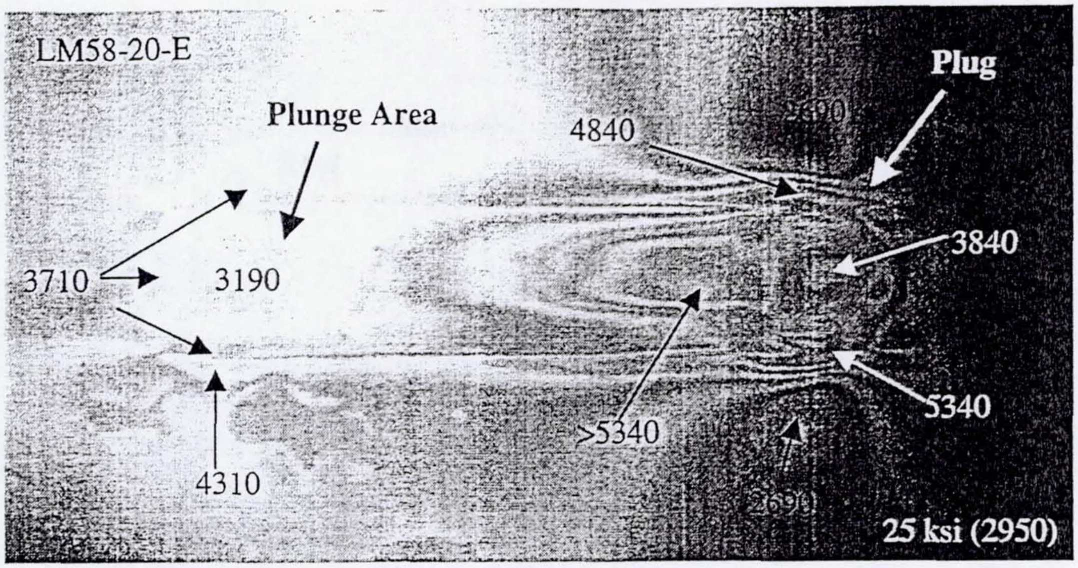

Figure 6. Isochromatic fringe pattern, Panel LM58-20-E, 25 ksi loading

(Values are in micro strain).

Table 2 lists mechanical property results for RT and CRYO testing of the repair scenarios. Also given are the 1.0" test results for the original as welded (AW) FSW of each test panel. Results show a minor effect (5% lower) due to specimen size for RT ultimate strength of 15-inch versus1.0-inch width specimens. RT ultimate strength for the fusion repair on the FSW was 36.8 ksi. a value typical of current fusion repairs to fusion welds.

At –423^{0}F, results varied based on the repair scenario simulated. As welded strength was about 8% lower than average (95.5ksi) for ultimate strength at –423^{0}F. The single Friction Plug Weld (FPW) repair was 11% lower. The FSW Repair with FPW closeout was 14% lower. Simulation of a FSW Overlap tested 23% lower than average. Finally, the simulation of a five-pass fusion weld repair of a FSW tested at 53.3ksi. While significantly less than other FSW repair methods. 53ksi ultimate is fairly typical of strength attained in current fusion weld repairs.

Table 2. Tensile Strength of 15" Wide FSW Repairs

Weld Method	RT (AW) Ftu (ksi) 1" W	RT (AW) %El 1" W	RT Ftu (ksi) 15" W	RT %El 15" W	Cryo Ftu (ksi) 15" W	Cryo %El 15" W
As Welded	57.2	10	55.0	11.9		
As Welded	59.8	15			87.6	----
FPW Repair	60.4	10.4	57.0	18.6		
FPW Repair	59.4	11.2			84.9	12.0
FSW Repair	59.3	9.9	55.7	13.5		
FSW Repair	59.8	14.6			82.6	11.0
Overlap FSW	59.7	15	56.9	16.0		
Overlap FSW	59.8	14.5			73.2	11.0
Fusion Repair	59.6	14.6	36.8	9.5		
Fusion Repair	59.9	13			53.3	8.3

Metallography of FSWelds

Macro and micro examination of specimens was conducted during the development testing for FSW. The macro features exhibited in a FSW are shown in Figure 7. The weldment consists of a single weld nugget with broad "flow arms" extending on either side of the weld centerline to a width equal to the diameter of the FSW pin tool. This region is the surface re-heated zone (SDXZ) which occurs on the Crown side where the weld tool interfaces with the weld material. Below the SDXZ is a rounded elliptical region of fine grain size equiaxed microstructure, the dynamically recrystallized zone (DXZ). Thermomechanical zones (TMZ) are adjacent to the DXZ on either side, and below the SDXZ. Beyond these regions is a heat affected zone (HAZ) extending into parent metal (PM).

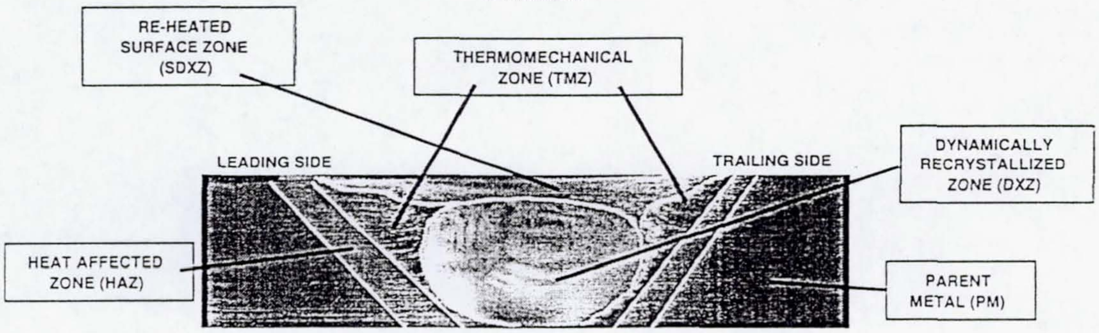

Figure 7. FSW full penetration microstructure in 0.32 Al2195-T8 Plate

NonDestructive Evaluation

Visual and NDE inspections were conducted post-weld on all FSW test panels and demonstration articles. Development and selection of appropriate NDE methods was concluded after a series of tests among five different methods. These tests involved varying types of post weld surface preparation, penetrants, developers, and radiographic and ultrasonic techniques. Visual, radiographic (RT) and Level III penetrant (PT) inspection were the resultant NDE baseline for FSW. Post weld surface preparation consists of removing the flash form the Crown side, sanding the Root side, and etching both sides for PT inspection.

In excess of 300 feet of FSW have been conducted with only one indication noted on the Crown side of the weld. This single indication was located where the weld flash had been pulled from the weld, as opposed to removal with a bead shaver. The result was a tear on the surface of the weld that was detected by both ultrasonic and dye penetrant inspections of the Crown side. Metallurgical evaluations confirmed these NDE results.

The same inspections were performed on the root side of the weld and have yielded only one type of flaw identified as Lack Of Penetration (LOP). LOP describes a *metallurgical condition* where un-recrystallized parent material remains below the DXZ which may be associated with a very tight cold lap at surface on the Root side. LOP is the combined distance extending from the edge of the DXZ to the bottom of the nugget.

LOP ties directly to one of the key process parameters - penetration ligament. Penetration ligament is a *process parameter*, which defines the offset distance between the tip of the pin tool and the back surface of the plate being welded. In a typical friction stir weld, the "dynamically

recrystallized zone" extends below the tip of the pin to the back surface of the plate. Therefore, a full penetration weld can be obtained even though the pin does not extend fully through the material being welded. A LOP flaw occurs when the DXZ does not extend completely through the FSW. Figure 8 illustrates an LOP flaw in 0.32" Al2195.

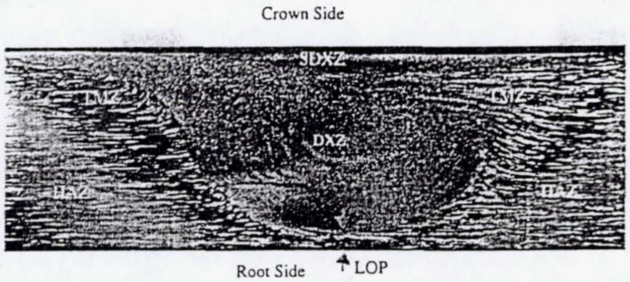

Figure 8. FSW showing LOP in 0.32" AL2195-T8 Plate

The presence of flaws is always a consideration in building aerospace hardware. It is for this reason, that multiple NDE inspections are conducted and designs are based on fracture mechanics principles such as fracture toughness.

Fracture Toughness – Surface Crack Tension (SCT)

Surface Crack Tension (SCT) testing was chosen to characterize the toughness of FSW specimens in 0.320" AL2195P-T8. Several flaw locations were tested in an effort to determine the worst case location, or the least toughness, in the friction stir weld. Tests were performed at RT, -320°F, and –423°F to further elucidate the fracture enhancement ratios at each flaw location.

Six different flaw locations and three flaw sizes were tested in an effort to characterize a wide range of SCT parameters, as illustrated in Figure 9 and listed in Table 3. All flaws were oriented parallel to the weld direction and perpendicular to the load direction. The flaws were initiated by EDM, then fatigued with cyclic axial tension to final size.

The Trailing Edge (TE) and Leading Edge (LE) Crown flaw locations resulted in the highest toughness at room temperature because these specimens tested mostly parent metal in the HAZ rather than the weaker nugget metal. Conversely, the Centerline (CL) flaws tested strictly the weld nugget, resulting in consistently lower toughness.

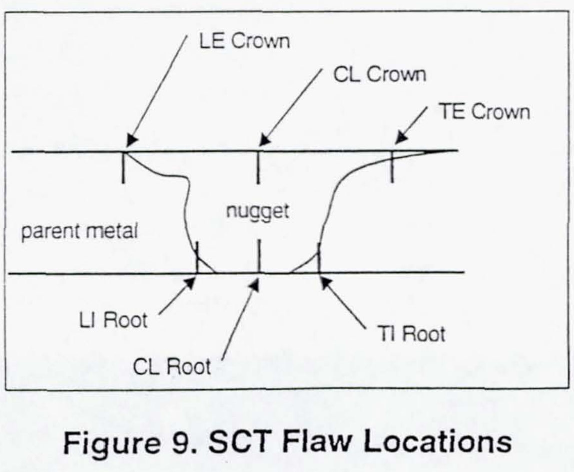

Figure 9. SCT Flaw Locations

Table 3. SCT Flaw Sizes

	Target Flaw Size	
a/2c Ratio	a (in)	2c (in)
0.50	0.125	0.250
	0.250	0.500
0.20	0.150	0.750

The Leading and Trailing Interface, (LI) and (TI) Root locations resulted in wide scatter in the toughness data. Since flaw location varied from the interface into the parent metal HAZ.

Gross fracture stress was characterized and plotted using the CL flaw test data in Figure 10. T date, the limited data yields a fitted curve with a sharp elbow at 59ksi asserting the weld is unaffected by flaws smaller than 0.180-inch in length for both a/2c=0.5 and a/2c=0.2.

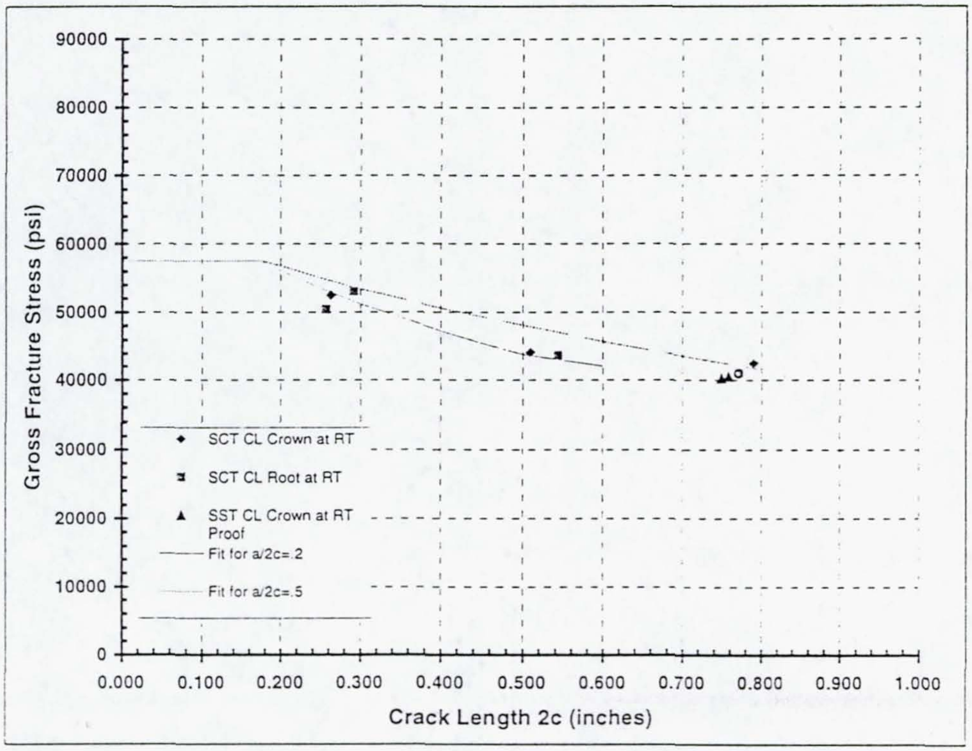

Figure 10. Curve fit to 0.320-inch Al2195P/2195P SCT results at room temperature.

SUMMARY

Mechanical property tests of FSW in 0.32" Al2195 resulted in an average room temperature ultimate tensile strength of 59 ksi, with a cryogenic (-423^0F) enhancement factor of 1.6 and elongation of 10% and above. Surface crack tension (SCT) tests resulted in gross fracture stress values well above the values associated with the current fusion weld processes. Potential FSW repair scenarios were successfully accomplished, with some reduction in weld tensile strength at both room and cryogenic temperatures dependent on the repair type.

NDE techniques were used for detecting both volumetric and surface defects present in friction stir welds. NDE and metallurgical results confirmed no internal volumetric defects present in the friction stir welds studied. The most significant potential defect observed was lack of penetration on the root side of the weld. Dye penetrant techniques were developed for detecting this defect, however the prevention of this defect lies in process control to assure adequate weld penetration.